ON THE VISCOSITY OF GASES AT HIGH EXHAUSTIONS[1]

BY the viscosity or internal friction of a gas is meant the resistance it offers to the gliding of one portion over another. In a paper read before the British Association in 1859 Maxwell[2] presented the remarkable result that on theoretical grounds the coefficient of friction, or the viscosity, should be independent of the density of the gas, although at the same time he stated that the only experiments he had met with on the subject did not seem to confirm his views.

An elaborate series of experiments were undertaken by Maxwell to test so remarkable a consequence of a mathematical theory; and in 1866, in the Bakerian lecture for that year,[3] he published the results under the title of "The Viscosity or Internal Friction of Air and other Gases." He found the coefficient of friction in air to be practically constant for pressures between 30 inches and 0·5 inch; in fact numbers calculated on the hypothesis that the viscosity was independent of the density agreed very well with the observed values.

The apparatus used by Maxwell was not of a character to admit of experiments with much lower pressures than 0·5 inch.

Maxwell's theory that the viscosity of a gas is independent of the density presupposes that the mean length of path of the molecules between their collisions is very small compared with the dimensions of the apparatus; but inasmuch as the mean length of path increases directly with the expansion, whilst the distance between the molecules only increases with the cube root of the expansion, it is not difficult with the Sprengel pump to produce an exhaustion in which the mean free path is measured by inches, and even feet,[4] and at exhaustions of this degree it is probable that Maxwell's law would not hold.

The experiments recorded in this paper were commenced early in 1876, and have been continued to the present time. In November, 1876, the author gave a note to the Royal Society on some preliminary results. Several different forms of apparatus have since been used one after the other, with improvements and complexities suggested by experience or rendered possible by the extra skill acquired in manipulation. The earlier observations are now of little value, but the time spent in their prosecution was not thrown away, as out of those experiments has grown the very complicated apparatus now finally adopted.

The Viscosity Torsion Apparatus, with which all the experiments here given have been performed, is a very complicated instrument. It consists essentially of a glass bulb, blown with a point at the lower end, and sealed on to a long narrow glass tube. In the bulb is suspended a plate of mica, by means of a fine fibre of glass 26 inches long, which is sealed to the top of the glass tube, and hangs vertically along its axis. The plate of mica is ignited and lamp-blacked over one-half. The tube is pointed at the upper end, the upper and lower points are 46 inches apart, and are accurately in the prolongation of the axis of the tube. Sockets are firmly fixed to a solid support, so that when the tube and bulb are clamped between them they are only able to move around the vertical axis. The glass fibre being only connected with the tube at the top, rotating the tube on its axis communicates torsion to the fibre, and sets the mica plate swinging on the same axis without giving it any pendulous movement. The diameter of the fibre is about 0·001 inch. The viscosity apparatus is connected to the pump by a flexible glass spiral, so as to allow the apparatus to rotate on the pivots and at the same time to be connected to the pump altogether with sealed glass joints. An arm working between metal stops limits the rotation to the small angle only which is necessary.

The torsional movement given to the mica plate by the light of the candle shining on it or by the rotation of the bulb and tube on its axis by the movement of the arm between the stops, is measured by a beam of light from a lamp, reflected from a mirror to a graduated scale.

The pump employe has already been described. The measuring apparatus is similar to that described by Prof. McLeod[1] before the Physical Society, June 13, 1874. As it contains several improvements shown by experience to be necessary when working at very high vacua, a detailed description is given in the paper.

When taking an observation the arm is moved over to the stop, and in a few seconds allowed to return to its original position by the action of a spring. This movement rotates the viscosity apparatus through a small angle, and sets the mica plate vibrating, the reflected line of light traversing from one side of the scale to the other in arcs of diminishing amplitude till it finally settles down once more at *zero*.

The observer watching the moving index of light records the scale number reached at the extremity of each arc. The numbers being alternately on one and the other side of zero are added two by two together, to get the value of each oscillation. The logarithms of these values are then found, and their differences taken; the mean of these differences is the logarithmic decrement per swing of the arc of oscillation. For the state of brevity this is called the log dec.

A very large number of experiments have been made on the viscosity of air and other gases. Observations have been taken at as high an exhaustion as 0·02 M, but at these high points they are not sufficiently concordant to be trustworthy. The pump will exhaust to this point without difficulty if a few precautions are taken, but at this low pressure the means of measuring fail in accuracy.

The precautions which experience shows to be necessary when exhausting to the highest points are fully described in the paper.

Viscosity of Air.—The mean of a very large number of closely concordant results gives as the log decrement for air for the special apparatus employed, at a pressure of 760 millims. of mercury and a temperature of 15° C., the number 0·1124. According to Maxwell the viscosity should remain constant until the rarefaction becomes so great that we are no longer at liberty to consider the mean free path of the molecules as practically insignificant in comparison with the dimensions of the vessels.

The author's observations show that this theoretical result of Maxwell's is at least approximately and may be accurately true in air up to comparatively high exhaustions; and that at higher exhaustions the viscosity falls off, as it might be expected to do according to theory.

The results are embodied in a table and diagrams.

The first half of the table gives the viscosity of air, in so far as it is represented by the log dec., at pressures intermediate between 760 millims. and 0·76 millim. (1000 millionths of an atmosphere). In order to avoid the inconvenience of frequent reference to small fractions of a millimetre, the millionth of an atmosphere[2] (= M) is now taken as the unit instead of the millimetre. The second half of the table is therefore given in millionths, going up to an exhaustion of 0·02 millionth of an atmosphere.[3]

Starting from the log dec. 0·1124 at 760 millims., the viscosity diminishes very regularly, but at a somewhat decreasing rate. Between 50 millims. and 3 millims. the direction is almost vertical, and a great change in the uniformity of the viscosity curve commences at a pressure of about 3 millims. At this point the previous approximation to, or coincidence with, Maxwell's law begins to fail, and further pumping considerably reduces the log decrement.

From 1000 M the diminution of viscosity is very slight until the exhaustion reaches about 250 M; after that it gets less with increasing rapidity, and falls away quickly after 35 M is reached.

The curves of increasing mean free path and diminishing viscosity closely agree. This agreement is more than a mere coincidence, and is likely to throw much light on the cause of viscosity of gases.

[1] Abstract of a paper read before the Royal Society, February 17, 1881, by William Crookes, F.R.S.

[2] *Phil. Mag.*, 4th ser. vol. xix. p. 31.

[3] *Phil. Trans.* 1866, part 1, p. 249.

[4] Thus, supposing the mean free path of the molecules of air at the ordinary pressure is the 1-10,000th of a millimetre, at an exhaustion of the ten-thousandth of an atmosphere, the mean free path will be 1 millim. At one-millionth of an atmosphere the mean free path will be 10 centimetres, and at an exhaustion of one hundred millionth—by no means a difficult point to attain with present appliances—the mean free path will be over 30 feet. This rarefaction corresponds to that of the atmosphere at a height above the earth of a little more than ninety miles, assuming that its density decreases in geometrical progression as its height increases in arithmetical progression, and neglecting the small corrections for diminished gravity and temperature. As the height above the earth increases, the length of the mean free path of the molecules of air rapidly approaches to planetary distances; at about 200 miles height the mean free path is 10 million miles, whilst between eighty and ninety miles higher the rarity is such that the mean free path would extend from here to Sirius.

[1] *Philosophical Magazine*, vol. xlviii. p. 110, August, 1874.

[2] M = 0·00076 millim.; 1315·789 M = 1 millim.

[3] To give some idea of the high exhaustions at which its measurements can be taken it may be mentioned that the highest exhaustion on the table—0·02 M—bears about the same proportion to the ordinary atmospheric pressure that 1 millimetre does to thirty miles, or, converting it into time, that one second bears to twenty months.

In the table is also given the measurements of the repulsion exerted on the blackened end of the mica plate by a candle-flame placed 500 millims. off. The repulsion due to radiation commences just at about the same degree of exhaustion where the viscosity begins to decline rapidly, and it principally comes in at the exhaustions above 1000 M.

The close agreement between the loss of viscosity and the increased action of radiation is very striking up to the 35 millionth, when the repulsion curve turns round and falls away as rapidly as the viscosity.

Experiments are next described on the resistance of air to the passage of an induction spark.

Since the publication of the author's researches on the phenomena presented by the passage of the induction discharge through high vacua, the present results—which, although never published, precede by a year or two those just mentioned—have lost much of their interest.

The phenomena at the very high exhaustion of 0·02 M may be of interest. With a coil giving a spark 85 millims. long, no discharge whatever passes. On increasing the battery power till the striking distance in air was 100 millims. the spark occasionally passed through as an intermittent flash, bringing out faint green phosphorescence on the glass round the end of the — pole.

On one occasion the author obtained a much higher exhaustion than 0·02 M. It could not be measured, but from the repulsion by radiation and the low log dec. it was probably about 0·01 M. The terminals of the vacuum tube and wires leading to them were well insulated, and the full power of a coil giving a 20-inch spark was put on to it. At first nothing was to be seen. Then a brilliant green light flashed through the tube, getting more and more frequent. Suddenly a spark passed from a wire to the glass tube, and pierced it, terminating the experiment.

Since these experiments vacua have frequently been got as high, and even higher, but the author has never seen one that would long resist a 20-inch spark from his large coil.

Viscosity of Oxygen.—The series of experiments with air show a complete history of its behaviour between very wide limits of pressure. It became interesting to see how the two components of air, oxygen and nitrogen, would behave under similar circumstances. Experiments were therefore instituted exactly as in the case of dry air, but with the apparatus filled with pure oxygen.

The results are given in the form of tables and plotted as curves on diagrams.

The figures show a great similarity to the air curve. Like it the log dec. sinks somewhat rapidly between pressures from 760 millims. to about 75 millims. It then remains almost steady, not varying much till a pressure of 16 millims. is reached. Here however it turns in the opposite direction, and increases up to 1·5 millim. It then diminishes again, and at higher exhaustions it rapidly sinks. This increase of viscosity at pressures of a few millimetres has been observed in other gases, but only to so small an extent as to be scarcely beyond the limits of experimental error. In the case of oxygen however the increase is too great to be entirely attributable to this cause.

Oxygen has more viscosity than any gas yet examined. The viscosity of air at 760 millims, being 0·1124, the proportion between that of air and oxygen, according to these results, is 1·1185.

This proportion of 1·1185 holds good (allowing for experimental errors) up to a pressure of about 20 millims. Between that point and 1 millim. variations occur, which have not been traced to any assignable cause: they seem large to be put down to "experimental errors." The discrepancies disappear again at an exhaustion of about 1 millim., and from that point to the highest hitherto reached the proportion of 1·1185 is fairly well maintained.

Viscosity of Nitrogen.—The proportion between the viscosities of nitrogen and air at a pressure of 760 millims is, according to these experiments, 0·9715.

A comparison of the air curves with those given by oxygen and nitrogen gives some interesting results. The composition of the atmosphere is, by bulk,

Oxygen	20·8
Nitrogen	79·2
	100·0

The viscosity of the two gases is almost exactly in the same proportion: thus at 760 millims—

$$\frac{20{\cdot}8 \ vis. \ \mathrm{O} + 79{\cdot}2 \ vis. \ \mathrm{N}}{100} = vis. \text{ air},$$

$$\frac{20{\cdot}8\,(0{\cdot}1257) + 79{\cdot}2\,(0{\cdot}1092)}{100} = \quad ,,$$

$$\frac{2{\cdot}61456 + 8{\cdot}64072}{100} = 0{\cdot}11255,$$

a result closely coinciding with 0·1124, the experimental result for air. Up to an exhaustion of about 30 M the same proportion between the viscosities of air, oxygen, and nitrogen is preserved with but little variation. From that point divergence occurs between the individual curves of the three gases.

Observations on the Spectrum of Nitrogen.—Spectrum observations during exhaustion give the following results:—

At 55 millims. pressure the band spectrum of nitrogen commences to be visible. The red and yellow bands are easily seen, and the green and blue are exceedingly faint. As the pressure grows less the bands become more distinct, until at 1·14 millim. the band spectrum is at its brightest.

At a little higher exhaustion a change comes over the spectrum, and traces of the line spectrum are observed.

At 812 M both the band and the line spectrum can be seen very brilliantly.

At 450 M the line spectrum is seen in great purity. As the exhaustion becomes higher the lines commence to disappear at the two ends of the spectrum.

At 188 M the lines below λ 610 ms. of m.m. at the red end, and above λ 400, cease to be visible.

At 94 M a bright greenish yellow line is visible at about λ 567.

At 55 M this greenish yellow line is still very prominent. The red lines have disappeared altogether, and the highest blue line visible is one at λ 419. The line 567 varies much in visibility; sometimes it cannot be seen, whilst at others it is very visible. Thus—

At 40 M the line 567 has quite disappeared.

At 17 M line 567 is visible again, being the most prominent line left.

At 12 M line 567 is not seen, although several other green and blue lines are left.

At 3 M only three lines are visible in the green, and these are very faint.

At 2·8 M line 567 is detected again.

At 2 M only traces of one or two lines can be seen, the faint light of the lines being overpowered by the green phosphorescence of the glass.

Line 567 has been seen on several occasions at high exhaustions when the gas under examination has been mixed with a little air. It is probably a nitrogen line, for one of the most brilliant nitrogen lines has a wave-length of 567·8 (Thalén), 568·0 (Huggins), or 568·1 (Plücker), and the author's interpolation curve is not sufficiently accurate to enable him to say that the line entered in as being at 567 may not in reality be a trifle higher. The reason of its being only sometimes visible may be accounted for by a difference in the sensitiveness of the eye at different times, or by a difference in battery power. This however cannot be the whole explanation, for other lines are not found to vary in the same manner.

The curve of Repulsion exerted by Radiation is much lower than in oxygen or air, and sinks rapidly after the maximum is passed.

Viscosity of Carbonic Anhydride.—The curves of this gas are given in diagrams plotted from the observations. At first the curve seems to follow the same direction as the air curve. But at a pressure of about 620 millims. it slopes more rapidly till the pressure is reduced to about 50 millims., when the curve again takes the direction of the air curve. The total diminution between 760 millims. and 1 millim. is nearly double that of air.

Observations have also been taken with the spectroscope during the exhaustion of carbonic anhydride. The maximum brilliancy of the spectrum occurs at an exhaustion of about 300 M. After that it gets fainter; at about 75 M the blue band (λ 409 to 408 ms. of mm.) disappears; as the exhaustion gets higher the other bands vanish until, at a vacuum of about 40 M, nothing is visible but the two lines λ 519 and λ 560. At higher exhaustions these lines disappear, and the phenomena of "Radiant Matter" commence.

The proportion between the viscosity of carbonic anhydride and air at 760 millims. is 0·9208.

Viscosity of Carbonic Oxide.—The results with this gas are remarkable as showing an almost complete identity with those of nitrogen both in position and shape. The viscosity at 760 millims. is in each case 0·1092.

Like that of nitrogen the curve of carbonic oxide is seen to be vertical—*i.e.*, assuming the curve to represent the viscosity, the gas obeys Maxwell's law, at pressures between 90 millims. and 3 millims. The straight portion in nitrogen is at a little higher pressure—between 100 millims. and 6 millims.

The curve of repulsion resulting from radiation is lower in carbonic oxide than in any other gas examined, and, unlike the other gases, there is no sudden rise to a maximum at about 40 M. At lower exhaustions the curve is, however, higher than it is in nitrogen.

During exhaustion observations were continued on the variations in the spectrum. The ordinary band spectrum is first seen with a few sharp lines terminating the bands.

At 12 millims. pressure a sharp green line is first seen, λ 515 ms of mm. This line rapidly grows brighter as exhaustion continues, and then fades out; it is last seen at a pressure of about 0·9 millim. This line is probably the bright oxygen-line, the wave-length of which is given by Plücker at 514·4.

At a pressure of 2·8 millims. the spectrum agrees in appearance with the "Carbon No. 2" in Watts's "Index of Spectra."

At 553 M the bands between the sharp lines appear to be breaking up into masses of fine lines.

At 211 M these fine lines are distinctly visible. The brightness of this spectrum is now near its maximum.

At 100 M the general spectrum is growing faint, but a sharp green line at λ 534 makes its appearance by fits and starts. This is coincident with Plücker's bright oxygen line λ 534.

After this degree of exhaustion the spectrum rapidly gets fainter. The line λ 534 soon disappears, and the carbon lines also go one after the other, until at an exhaustion of 4 M only two lines are visible, λ 560 and λ 519.

Viscosity of Hydrogen.—It has been found that hydrogen has much less viscosity than any other gas; the fact of the log dec. not decreasing by additional attempts at purification is the test of its being free from admixture. This method of ascertaining the purity of the gas, by the uniformity of its viscosity coefficient at 760 millims., is more accurate than collecting samples and analysing them eudiometrically.

Several series of observations in hydrogen have been taken. For a long time it was considered that hydrogen, like other gases, showed the same slight departure from Maxwell's law of viscosity being independent of density that appeared to be indicated with other gases; for the log dec. persistently diminished as the exhaustion increased, even at such moderate pressures as could be measured by the barometer gauge. Had it not been that the rate of decrease was not uniform in the different series of observations, it might have been considered that this variation from Maxwell's law was due to some inherent property of all gases. After working at the subject for more than a year it was discovered that the discrepancy arose from a trace of water obstinately held by the hydrogen. Since discovering this property extra precautions (already described at the commencement of the paper) have been taken to dry all gases before entering the apparatus.

The remarkable character of hydrogen is the uniformity of resistance which it presents. It obeys Maxwell's law almost absolutely up to an exhaustion of about 700 m., and then it commences to break down. Up to this point the line of viscosity is almost perfectly vertical. It then commences to curve over, and when the mean free path assumes proportions comparable with the dimensions of the bulb and approaches infinity, the viscosity curve in like manner draws near the zero line.

The repulsive force of radiation is higher in hydrogen than in any other gas. It commences at as low an exhaustion as 14 millims., but does not increase to any great extent till an exhaustion of 200 M is attained; it then rises rapidly to a maximum at between 40 and 60 M, after which it falls away to zero. The maximum repulsion exerted by radiation in hydrogen is to that in air as 70 to 42·6. This fact is now utilised in the construction of radiometers and similar instruments when great sensitiveness is required.

Taking the viscosity of air at 760 millims. as 0·1124, and hydrogen as 0·0499, the proportion between them is 0·4439.

The Spectrum of Hydrogen.—The red line (λ = 656), the green line (λ = 486), and the blue line (λ = 434) are seen at their brightest at a pressure of about 3 millims., and after that exhaustion they begin to diminish in intensity. As exhaustion proceeds a variation in visibility of the three lines is observed. Thus at 36 millims. the red line is seen brightly, the green faintly, whilst the blue line cannot be detected. At 15 millims. the blue line is seen, and the three keep visible till an exhaustion of 418 M is reached, when the blue line becomes difficult to see. At 38 M only the red and green lines are visible, the red being very faint. It is seen with increasing difficulty up to an exhaustion of 2 M, when it can be seen no longer. The green line now remains visible up to an exhaustion of 0·37 M, beyond which it has not been seen.

It is worthy of remark that although when working with pure hydrogen the green line is always the last to go, it is not the first to appear when hydrogen is present as an impurity in other gases. Thus, when working with carbonic anhydride insufficiently purified, the red hydrogen line is often seen, but never the green or the blue line.

(*To be continued.*)

SEEING BY ELECTRICITY[1]

ON being called upon by the chairman to show his experiments, Prof. Ayrton stated that he and Mr. Perry thought that the occasion of the reading of Mr. Bidwell's paper was a suitable one for their showing to the Society that they were constructing the apparatus described by them in a letter in NATURE, vol. xxii. p. 31. The feasibility of their plan had been combated, and at the last meeting of the British Association at Swansea it was confidently asserted that the action of selenium was not quick enough to register rapid changes of light intensity—an idea, however, which they stated in the discussion at the time there was experimental evidence to disprove. After that came the publication and exhibition of the photophone, proving that selenium changed its electrical properties synchronously with rapid changes in light intensity. For a light telegraph however not only was this property necessary, but in addition that the electric changes in the selenium should be considerable for a comparatively small change in the light. They had, therefore, tried to make sensitive selenium cells of low resistance. The method they had employed consisted in winding two wires parallel on strips of box-wood, ivory, and other non-conductors in section, somewhat like that of a paper-knife in the manner subsequently described by Mr. Bidwell in NATURE, but they had not found it necessary to cut a screw on the wood or mica in a lathe. Of the twenty-five cells that they had constructed they had invariably found, like Mr. Bidwell, that only those were sensitive that had a high resistance. They were aware that Prof. Adams had made sensitive cells of low resistance, and had he been present they would have liked to ask whether it was not only for very small electromotive forces that the cells were sensitive. They had also found that when sensitive cells of 100,000 ohms resistance diminished in resistance to only a few hundred ohms by natural annealing extending over some months, the cells lost entirely their sensibility. Further that certain sensitive cells of high resistance were sensitive as long as an electromotive force of not more than about seven volts was employed to send a current through them, but for electromotive forces much above this the cells were comparatively unsensitive to light, but the sensibility was not destroyed for electromotive forces smaller than seven volts used subsequently. These phenomena, which they believed had not been previously noticed, pointed, they suggested, to the sensibility of selenium being due almost entirely to a polarisation and not merely to a change of resistance, as was commonly supposed and stated. Might it not be possible, they asked, that there was an electromotive force developed in selenium by light, which, for different cells, increased more rapidly than the resistance of the cell, and which was the greater, the greater the electromotive force of the auxiliary battery employed; that in fact selenium became rapidly polarised by the auxiliary current flowing through it, and that this polarisation, the amount of which depended on this current, was removed in proportion to the intensity of the light. That a small electromotive force was developed in selenium by light when no auxiliary current was sent through it, had been conclusively shown by Prof. Adams and Mr. Day in 1876, a result that they had also experienced; and they would mention that a careful examination which they had recently made of the paper published by Prof. Adams and

[1] Paper communicated to the Physical Society, February 26.